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Plasma Motor Generator System

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| Prepared by: | Gerald E. Hite |
| Academic Rank: | Associate Professor |
| University & Department: | Texas A&M University at Galveston Department of Marine Science |

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| JSC Colleague: | James E. McCoy |
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PLASMA MOTOR GENERATOR SYSTEM

Gerald E. Hite
Associate Professor
Department of Marine Science
Texas A&M University at Galveston
Galveston, TX 77553

The significant potential advantages of a plasma motor generator system over conventional systems for the generation of electrical power and propulsion for spacecraft in low earth orbits warrants its further investigation. The two main components of such a system are a long (~10km) insulated wire and the plasma generating hollow cathodes needed to maintain electrical contact with the ionosphere.

Results of preliminary theoretical and experimental investigations of this system are presented. The theoretical work involved the equilibrium configurations of the wire and the nature of small oscillations about these equilibrium positions. A particularly interesting result was that two different configurations are allowed when the current is above a critical value.

Experimental investigations were made of the optimal starting and running conditions for the proposed, low current hollow cathodes. Although optimal ranges of temperature, argon pressure and discharge voltage were identified, start-up became progressively more difficult. This supposed depletion or contamination of the emissive surface could be countered by the addition of new emissive material. The sharp transition between the two distinctively different working modes of these hollow cathodes was studied extensively. It is proposed that this transition is due to the establishment in the orifice of a plasma distinct from that inside the hollow cathode.

NASA Colleague: James E. McCoy, SN3, x5171

I. INTRODUCTION

According to Faraday's law of induction, a voltage will be induced in a wire which moves across magnetic field lines. Provided there is a stationary return path for current, electrical power can be extracted (an $I \times B$ force will act to reduce the relative speed of the wire with respect to the magnetic field), or with the application of a reversed voltage greater than the induced voltage, electrical power will be expended and propulsion will result. In low Earth orbit a 10-kilometer long wire would have an induced voltage of slightly more than 2 kV. Neglecting losses and assuming good electrical contact with the ionosphere, 20 kw of power would be equivalent to a propulsion thrust of about 2.5 N. (1)

If there is no current in the wire and the spacecraft is in a circular orbit, then the combined effects of gravity and centripetal acceleration will cause the wire to hang either straight down or vertically upward. However, when a current flows, the $I \times B$ force will pull the wire from the vertical direction and there will be one, two, or no stable configuration, depending on the magnitude of the current. Clearly, knowledge of these configurations, and of the nature of small oscillations about these configurations, is essential to ensure the integrity of such power/propulsion systems.

The essential elements in the proposed system is the establishment of good electrical contact with the ionosphere. The most convenient way to establish this contact is with a plasma generator capable of producing plasma in such quantities

that it will exceed the ionosphere plasma out to a distance of ten meters or so. Hollow cathodes are known to be copious producers of plasma and have the potential to act as contractors. (2-5) Electrical power/propulsion systems using plasma contactors are generally called Plasma Motor/Generators (PMG).

In the past, hollow cathodes have served as plasma generators in Kaufman thrusters and similar ion propulsion systems. (6) In contrast to previous applications which needed massive ions (e.g., Hg) for propulsion, in this application the emphasis is on the quantity of plasma and thus harmless inert gases suffice as plasma stock. The present need is for low discharge current (~1A), high gas-flow (30 st. cc/min.) hollow cathodes. It is anticipated that little or none of the extensive magnetic field hardware associated with Kaufman thrusters will be necessary. Considerable research is now being done to test the performance of rugged, striped down hollow cathodes for a PMG system. Preliminary experimental testing has demonstrated that two plasma generators running at opposite ends of a vacuum chamber can generate plasmas sufficient to carry several amps of current between them. (7)

The internal dynamics of hollow cathodes are at best only partially understood. (2-5,8,9) At least two distinct running modes are described in the literature. (4,5,9) At low gas flow, hollow cathodes running in the "Plume" mode are characterized by an illuminous plume emanating from the cathode. With increasing gas flow, a value of the internal pressure is reached at which the plume is replaced suddenly by a glowing spot in the orifice

of the cathode, and the discharge voltage required to maintain constant discharge current jumps to a much lower value. This later, low voltage, high gas flow in general, more stable mode (Spot mode) is the preferred mode for a PMG contactor.

Clearly, optional starting conditions for these newer hollow cathodes need to be established to ensure the reliability of a PGM system. There is a long-standing problem of deterioration of hollow cathodes exposed to moisture and other contaminants normally avoided in laboratory environments. Care must be taken to ensure the purity and concentration of the emissive material in the hollow cathodes used in PMG systems.

This report will concentrate on theoretical results concerning configurations and small oscillations of PMG tethers and on experimental studies of optimal starting and running conditions of the cathodes especially designed and constructed for a PMG system by James E. McCoy at NASA Johnson Space Center.

II. CONFIGURATIONS OF AN ELECTRODYNAMIC TETHER

The equilibrium configuration of an electrodynamic tether can be found by considering the forces on an arbitrary, infinitesimal, segment of the tether. It will be convenient to consider a coordinate system moving with the spacecraft which will be assumed to be in a circular, low-earth orbit and to use the following symbols:

- B = component of magnetic field cut by tether
- g = acceleration due to gravity at orbit
- I = current in tether

L = length of tether

R = radius of orbit

T(x) = tension in tether

Ts = tension due to possible subsatellite on end of tether

x = radial distance measured from spacecraft

X = projection of tether on x-axis

$\theta(x)$ = angle of tether measured with respect to x-axis

ω = angular speed of the spacecraft

μ = mass per unit length of the tether

The sum of forces acting on such a segment, i.e., drag force, tensions on its ends, gravitational force, and the electromagnetic force, $I \times B$, must equal the mass times the acceleration. (The drag force can be neglected for the thin wires proposed for the tether.) The acceleration will be separated into a centripetal term and an acceleration with respect to the spacecraft. The centripetal term can be subtracted from the gravitational force to give a "force" which vanishes at the spacecraft.

Assuming a simple fall off of the gravitational force and using the coordinates system shown in Figure 1, the effect of gravity and centripetal acceleration for a mass, m, of tether is:

$$\begin{aligned} F_g &= mg(R/r)^2 - m\omega^2 r \quad , r = R-x \\ (1) \quad &= 3mg\left(\frac{x}{R}\right) + O\left(\left(\frac{x}{R}\right)^4\right) \end{aligned}$$

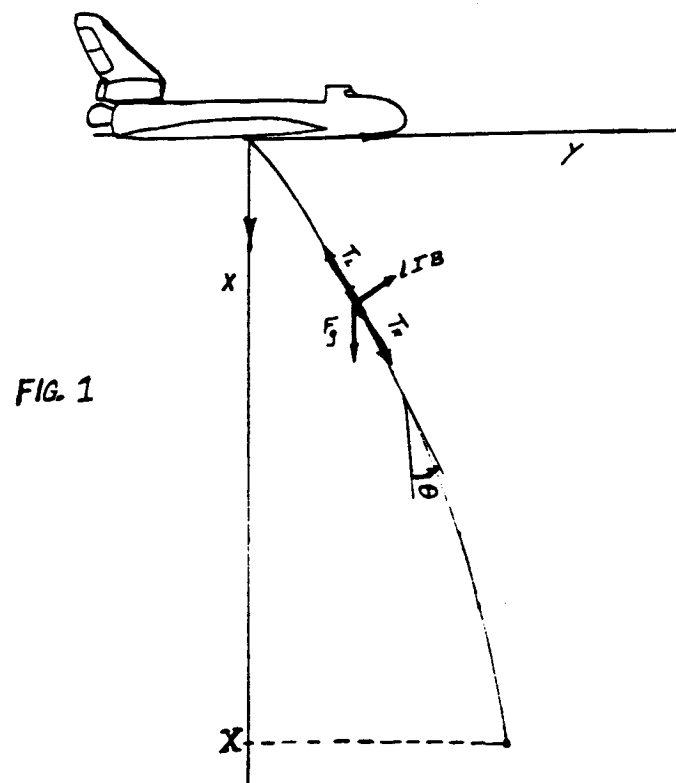
The equations of motion for a piece of tether of mass, m, and

length, l , are:

$$(2a) \quad F_g + T_R \cos \theta_R - T_L \cos \theta_L - IBL \sin \theta = m\ddot{x}$$

$$(2b) \quad IBL \cos \theta + T_R \sin \theta_R - T_L \sin \theta_L = m\ddot{y}$$

where the subscripts R and L indicate the values at the right and left ends of the segment shown in Figure 1.



Expanding equation (2) in $\Delta x (= l \cos \theta)$ and retaining first order terms as Δx goes to zero yields:

$$(3a) \quad 3\mu g \left(\frac{x}{R}\right) + \partial_x T = \mu (\ddot{y} \sin \theta + \ddot{x} \cos \theta) / \cos \theta = \mu \ddot{x}_{//} / \cos \theta$$

$$(3b) \quad IB + \partial_x (T \sin \theta) = \mu \ddot{y} / \cos \theta$$

where $\ddot{x}_{//}$ is the acceleration in the direction of the tether.

The static configurations are obtained by setting the accelerations in equation (3) equal to zero. The first equation yields the tension:

$$(4a) \quad T(x) = \frac{3}{2} \left(\frac{\mu g}{R}\right) (X^2 - x^2) + T_s$$

while the second equation gives:

$$(4b) \quad T \sin \theta = IB \cdot (X - x)$$

Clearly, the tension or $\sin \theta$ vanish at the far end of the tether. In the case when the subsatellite has negligible mass equation (4) yields:

$$(5) \quad \sin \theta = a / (X + x)$$

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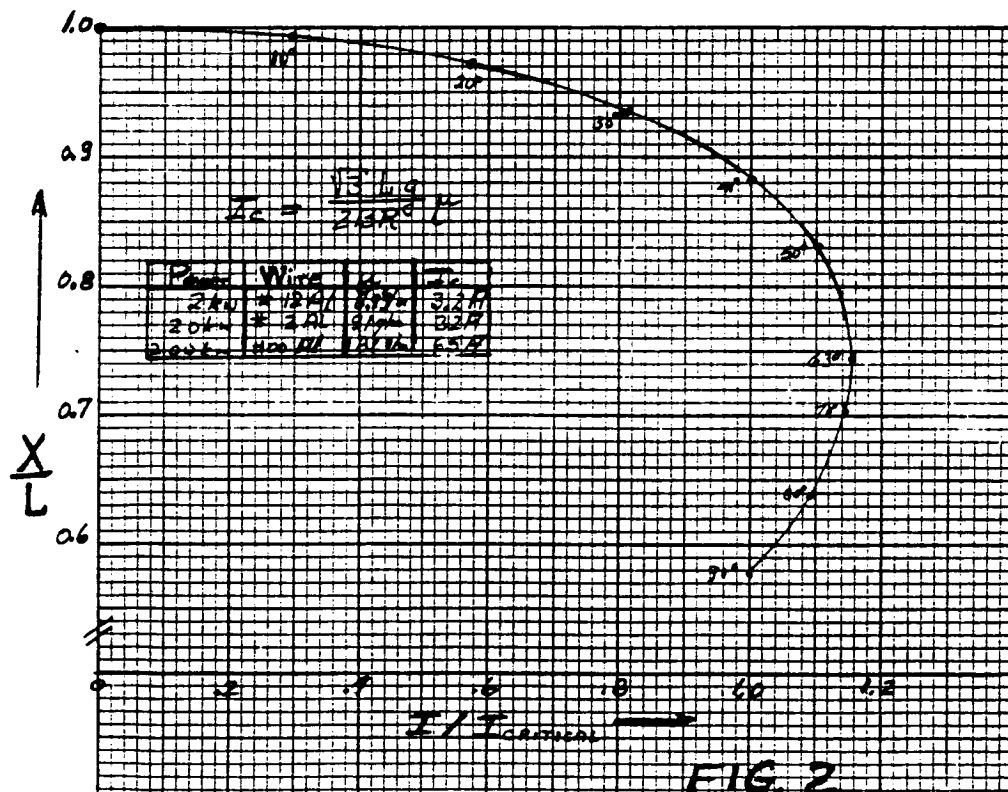
where $a/L = (2BR/3Mg) \cdot I = I/(\sqrt{3} I_c)$

The projection of the tether on the x-axis, X, can be related to the tether length, L, by:

$$(6) \quad L = \int_0^X dx / \cos \theta$$

In the absence of a subsatellite, this integral gives:

$$(7) \quad L/a = \sqrt{\left(\frac{2X}{a}\right)^2 - 1} - \sqrt{\left(\frac{X}{a}\right)^2 - 1}$$



A plot of I/I_c versus X/L is shown in Figure 2. For values of current less than I_c , there is one value of X and thus one stable configuration. For the current between I_c and $I_c \frac{2}{\sqrt{3}}$, there are two possible values of X and thus two distinct configurations. For still larger currents, the tether does not have a stable configuration and rotates around the spacecraft. Also shown in Figure 2 are the values of θ at the point of attachment on the spacecraft for each configuration.

Although no analytic solution for X was found for nonzero values of T_s , it is reasonable to assume that a small subsatellite would only effect the far end of the tether and that the essential features of the above discussion would still be true.

The nature of small oscillations about the stable configurations can be obtained from equation (3). For small oscillations the tether will be essentially only displaced perpendicular to its stable position, i.e., the right side of equation (3a) is zero and the tension will still be given by equation (4a). The normal procedure is now to replace $\sin \theta$ by $\tan \theta = \partial_x y$ which is the small angle approximation. Since for the tethers considered the current will be much smaller than I_c , the small angle approximation will be acceptable. Using this replacement and letting \tilde{y} be the displacement away from the stable configuration, equation (3b) reduces to:

$$(8) \quad \ddot{\tilde{y}} = \frac{1}{\mu} \partial_x (T \partial_x \tilde{y}) = \frac{3}{2} \left(\frac{g X^2}{R} \right) \partial_x \left(1 - \frac{X^2}{R} \right) \partial_x \tilde{y}$$

Assuming harmonic solutions, the solution for \tilde{y} is given by Legendre polynomials of odd order, i.e.,

$$(9a) \quad \tilde{y} = \tilde{y}_0 \cos \omega_e t \cdot P_l\left(\frac{x}{X}\right), \quad l = 1, 3, 5, \dots$$

where

$$(9b) \quad \omega_e^2 = \frac{3}{2} \left(\frac{g}{R}\right) l(l+1)$$

The frequency of small oscillation is just the square root of an *integer* times the orbital angular frequency. The excitation energy is given by:

$$(9c) \quad \mathcal{E}_e = \int_0^X \frac{1}{2} \mu (\omega \tilde{y}_0)^2 dx = 3 \left(\frac{M_g}{R}\right) \left(\frac{X}{L}\right) \tilde{y}_0^2 \frac{l(l+1)}{2l+1}$$

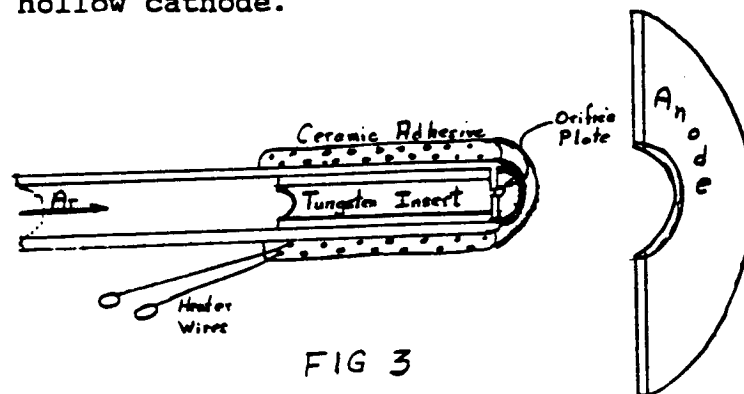
The amplitude \tilde{y}_0 is the maximum displacement at the far end of the tether from equilibrium.

The above results is exact for small values of the current, e.g., a fraction of I_c . For values up to I_c equations (9) should still give approximate results. The existence of two configurations for I larger than I_c would imply that if sufficient oscillatory energy were available, the tether would swing over a wide region containing both configurations.

All such oscillations could be reduced by applying an AC voltage to the tether with the resonance frequency but lagging by 90° . This would be just the opposite situation to that of a forced oscillator where the driving force leads by 90° at resonance. A more complicated means of dampening oscillations involves changing the length of the tether.

III. The Plasma Generator

The required electrical contact with the ionosphere for a PMG system could be maintained through the plasma generated by a low power, high gas flow, rugged hollow cathode running on a noble gas such as argon. Fig. 3 shows a cross-sectional view of the proposed hollow cathode.



The external heater wires heat the cathode to over 1000°C . The porous tungsten insert is originally impregnated with BaCO_3 and SrCO_3 . The gas carrying tube is made from tantalum, the orifice plate of tungsten, and the anode of molybdenum.

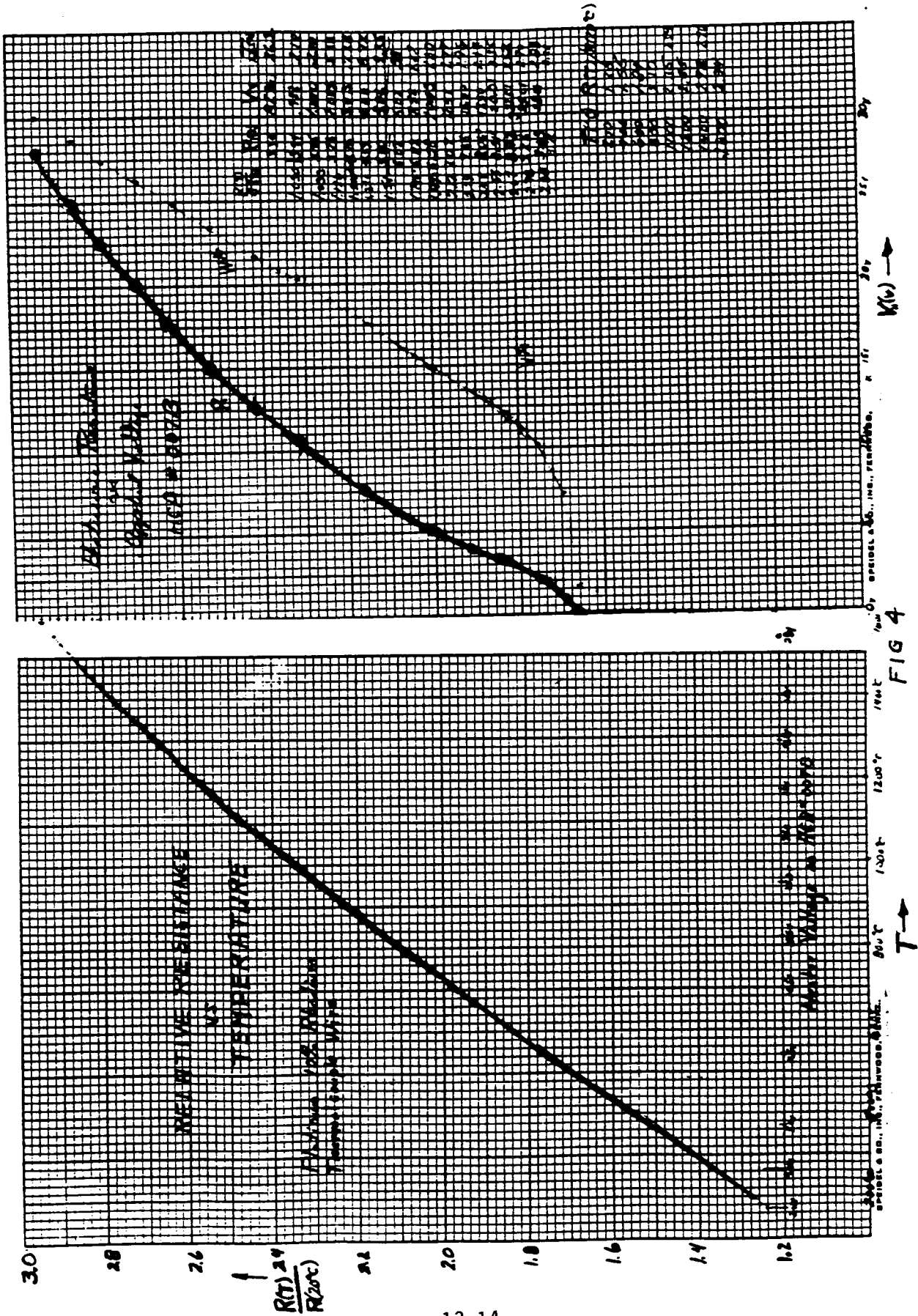
It is believed that the initial heating converts the BaCO_3 and SrCO_3 into BaO and SrO . Such alkaline earth compounds have very low work functions and are able at high temperatures to thermally (with possible assistance from sheath induced electric fields) emit electrons. ⁽⁵⁾ The electrons accelerated by electric fields obtain sufficient energy to ionize the neutral gas atoms either by single or multiple step processes.

The proposed heater is designed to be simple and rugged. The heating wire is 90° tungsten-10% sodium thermal couple wire. Consequently, the variation of its resistivity with temperature

is known. By measuring the resistance of the heater at each voltage setting, i.e., $V_{\text{heater}}/I_{\text{heater}}$, and normalizing by the value at room temperature, it is possible to determine the temperature of the heating wire for each voltage setting. As shown in Fig. 4, the temperature corresponding to the normal heating voltage (28v) is about 1550°C. Clearly a large percentage of the heat is being radiated outward and lost. A tantalum foil jacket could be put around the heater to conserve heat, but it was considered to be an unnecessary complication that could reduce the sturdiness of the plasma generator.

The small orifice (15 mil. dia) in the orifice plate enables the hollow cathode to have a relatively high internal pressure (150mm) appropriate to the optimal running conditions at the high gas flow normally used (30 st. cc/min).

Optimal starting conditions were established for the four identical hollow cathodes tested. It was found that a heating voltage of 28v (i.e., ca. 80 watts), and an internal pressure of approximately 130mm would allow a fresh hollow cathode to start spontaneously in the desired mode of operation (spot mode). However, after several starts and/or an accumulated running time (on the order of a few hours), the hollow cathodes became progressively harder to start and eventually refused to start spontaneously. Difficult starts were accompanied with large flashing plumes, spitting of "sparks" from the orifice, etc. Once running, no apparent deviation from normal operation was observed. To date, it has not been possible to find the cause of this deterioration. Similar degradation of hollow cathodes using



alkaline earth oxides has been observed and studied. (10) This supposed depletion or contamination of the emissive surface could be countered by the addition of new emission material. In some cases, starting could be initiated by increasing the internal gas pressure to over 200mm. Since the vacuum system could not handle such flow rates for long, reliability of this method was not pursued. Starting was possible in nearly all cases, if a 3 kv spark located near the anode was excited two or three times. Similar starts were induced by turning on an ion-vacuum gauge or a second hollow cathode elsewhere in the chamber. Apparently, the ions of such plasmas would travel to the cathode and affect the emission conditions or possible space charge configurations sufficiently to allow the hollow cathode to start.

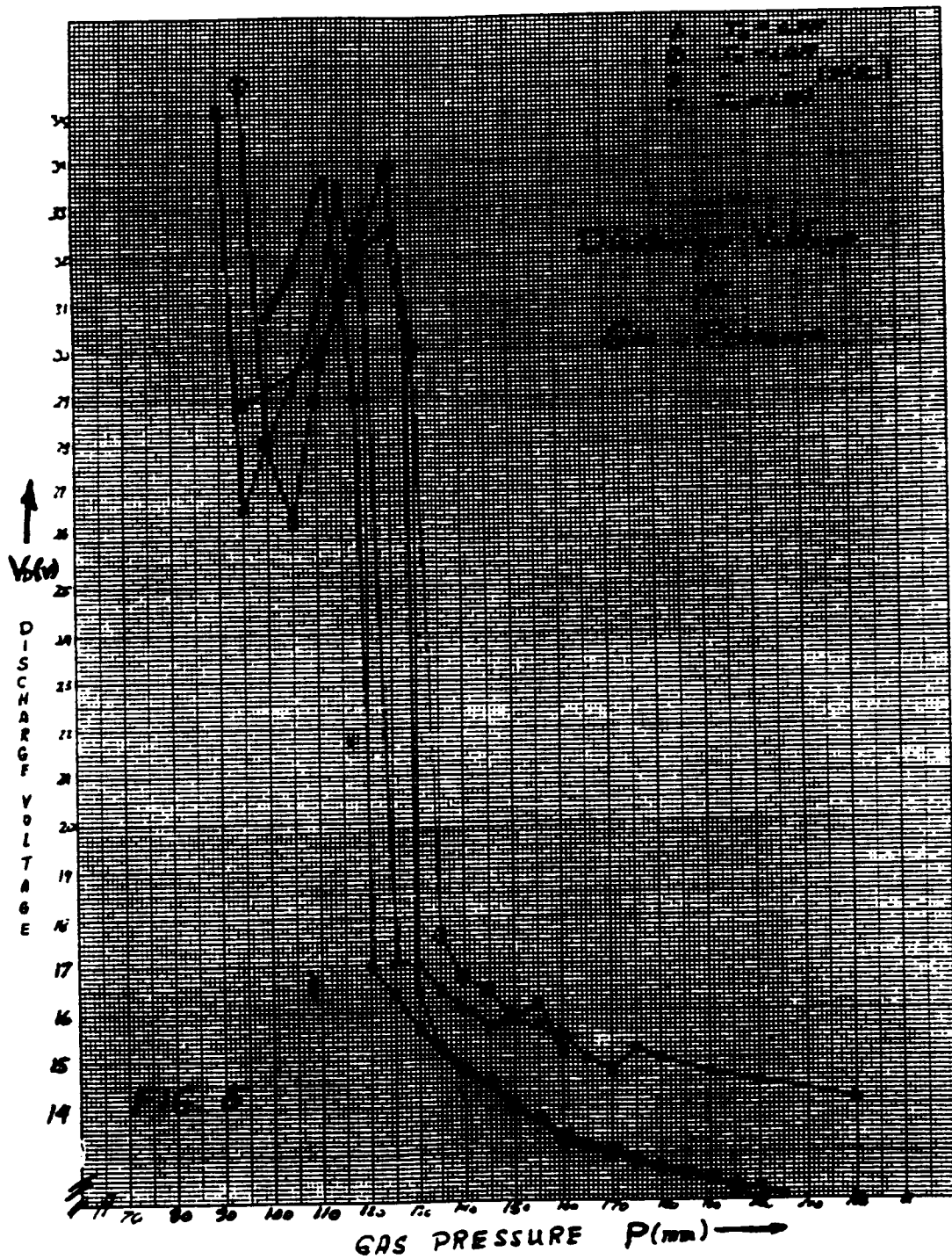
A model of how externally produced ions could initiate emission has been proposed. (7) Such ions would impinge on the outer surface of the orifice plate and initiate emission there. Assuming that emissive material migrates from the insert inside the cathode, through the orifice and onto the orifice plate, such emissive regions would tend to migrate to regions of increasing concentrations of emissive material, which would be in the direction of the orifice. Consequently, the emissive region and its accompanying and growing sheath would migrate into the orifice and, if conditions are favorable, into the interior of the cathode. Support for this explanation comes from the fact that a high voltage, low discharge (mA), is often observed before ignition even with no gas flow. During such discharges, a small (2-3 mm long) plume is often seen coming off the orifice plate.

In one case, it was at the position where emissive material had leaked out of the orifice after such material had been injected into the interior of the cathode.

Extensive investigations were made of the optimal running conditions for the PMG hollow cathodes. In general, most hollow cathodes have two distinct modes of operations. 2-5, 7-10 At low gas flow rates and internal pressure, hollow cathodes usually are running in the so-called plume mode, in which a blue plume is seen emanating from the orifice and extending to, or in some cases, past the anode. The shape and position of the anode influences the plume. As the external gas pressure is increased, a characteristic, transition value is reached at which the plume vanishes and leaves a bright glowing spot in the orifice (hence the name spot mode). Whereas before the transition the discharge voltage required for constant discharge current is decreasing, during the transition it falls abruptly to half of its value before the transition. The data shown in Fig. 5 shows the transition as the gas pressure is decreased. Although the spot mode is more stable mode than the plume mode, the instability of the plume mode in Fig. 5 is accentuated by gas pressure being changed too fast to allow the system to obtain complete thermal equilibrium.

The spot mode is a high gas flow, low power consumption mode. However, measurements have shown that the ratio of ion production to power consumption appears to be the same for both modes for other hollow cathodes. (7) Undoubtedly more experimental investigations must be made on the plasmas produced

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in the two modes before a final decision can be made on the optimal running mode for the PMG hollow cathode.

Extensive modeling of the internal dynamics of hollow cathodes running at low gas flow rates has been done. (2,5,8) Measurements of potentials have indicated that a potential of 8-12 volts is maintained inside the cathode just behind the orifice plate by an ion sheath surrounding a plasma in that region.⁽⁵⁾ The upstream extent of the plasma was on the order of a few millimeters and was observed to decrease with increasing pressure. Oscillations of the discharge currents have been observed at pressure just above the transition pressure and attributed to oscillations of a sheath in the orifice. (11) It is known that such sheaths are formed when electrons are confined to flow through a constriction or orifice. (12) Since the hollow cathodes used in this investigation have run at discharge voltages as low as 5 or 6 volts in the spot mode, it is reasonable to speculate that the plasma in the tube during the plume mode is compressed into a shorter and shorter cylinder and is abruptly forced out of the gas tube and into the orifice. As discussed before, it is reasonable to assume that emissive material has migrated into the orifice and consequently emissions could easily take place from the walls of the orifice. Due to the higher densities in the orifice, the plasma there would be distinctively different from that in the gas tube during plume mode. It is possible that the formation of the orifice plasma and the subsequent emission in the orifice characterizes the onset of the spot mode without complete cessation of emissions

inside the gas tube. The appearance of the bright spot in the orifice characterizing the spot mode could be due to dynamical effects taking place in the downstream boundary of the plasma in the orifice.

In conclusion, it is conjectured that the transition from plume to spot mode is characterized by the formation of an orifice plasma and subsequent field-enhanced thermionic emission from the orifice.

IV. Conclusions

A brief description of the proposed Plasma Motor/Generator system was given. Special attention was paid to the configuration and oscillations of the wire tether and to the starting and running conditions of the hollow cathodes designed to produce the plasma necessary for electrical contact with the ionosphere.

In studying the tether configurations it was found that there could be one, two, or none depending on the strength of the current. Small oscillations about the configurations anticipated in the proposed system were studied. Their form, frequencies and energies were found. Of the two methods of dampening such oscillations, the use of an AC source tuned to the resonance frequency was preferred.

It was concluded from experimental tests that starting of the PMG hollow cathode could be ensured by either frequent introductions of new emissive material or the use of a device capable of generating a seed plasma such as a sparker. A model

was proposed to explain the dynamical difference between the two distinct running modes observed in the PMG hollow cathode.

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